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Practical approach to water system optimal operation

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Abstract

Optimal pump scheduling is a major consideration when dealing with minimizing operational costs of a water distribution system. Pump operation must balance between three factors. Water balance constraints, including consumer demand and water tank volumes. Hydraulic constraints determining water pump operating point. Electrical tariff rate effecting energy cost.
Optimization models may assume linear or discrete pump operation, depending on type and accuracy of the model in use. Linear operation assumes the pump may operate during part of the time step while discrete operation requires the pump to be either on or off during the entire time step. Linear optimization models commonly have short solution times, but cannot contain non-linear constraints such as hydraulic headloss. By such, linear model results may be difficult to implement in a real water system as the hydraulic behavior of the system may render the optimal solution impractical. Likewise, if the pump operation partially uses the time step the pump may be forced to come in and out of duty often causing mechanical ware and tare.
Discrete operation provides smooth pump operation and may contain non-linear hydraulic constraint to calculate a more realistic working point for the pump. Discrete models have long solution times due the vast amount of pump operating combinations, which must be explored. Heuristic techniques may be used to shorten solution times but these do not assure global minimization of the solution.
The goal of the research is to create a minimum cost optimal operation water distribution system model that utilizes the short solution time of a linear model but also includes non-linear hydraulic constraints effecting pump energy consumption and discrete pump operation. The motivation is to use the model for real-time pump scheduling and for water system design.

Keywords: Discrete pump scheduling; Water distribution network optimal operation; Water headloss;

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1. Introduction

Pump scheduling is a major consideration in optimal water system operation. A linear optimization approach normally benefits from short solution times but suffers from the ability to handle only linear constraints. Also, the resulting pump scheduling may cause the pump to operation in only a partial part of the time step (hours) causing the pump to switch in and out of operation over consecutive time steps. This may result in increased mechanical wear of the pump and complex scheduling which is hard to apply in control centers.

Non-linear models may enjoy non-linear constraints better simulating water systems consideration such a water head and headloss, and accurate pump station energy consumption linked to operation dependent upstream and downstream hydraulic conditions. Such models may be solved using NLP solvers but also result in linear pump scheduling and commonly have long solution times. Discrete pump operation requires the use of MIP solvers or heuristic methods. Such models have long solution times relative to LP solvers and do not guaranty global minimization.

Since 1970 a variety of methods were developed to address the subject of optimal operation. Such means included the use of dynamic programming, linear programming, predictive control, mixed-integer, non-linear programming, metamodeling, heuristics, and evolutionary computation. A classification of optimal water distribution systems control models through systems type, hydraulics, and solution methods where presented to that time by Ormsbee and Lansey (1994).

This research proposes an iterative indexing approach for discrete pump operation, utilizing an iterative linearization method proposed by Price and Ostfeld (2013) to handle non-linear constraints. The result is an iteratively solved, minimal operating cost LP model combining: linear water balance constraints, non-linear convex headloss and water head constraints, and non-linear hydraulically dependent pump energy consumption.

Nomenclature

$Ah^t_{i,j}$	headloss linear equation coefficient, parameter.
$Ap^t_{i,j}$	energy consumption linear equation coefficient, parameter.
$Bh^t_{i,j}$	headloss linear equation coefficient, parameter.
$Bp^t_{i,j}$	energy consumption linear equation coefficient, parameter.
$C_{i,j}$	pipe roughness coefficient, constant (-).
$dH^t_{i,j}$	headloss in pipe, variable (m).
$D_{i,j}$	pipe diameter, constant (mm).
G	set of network arcs.
E^t_p	pumps energy consumption, variable (kWhr).
i,j	network node index.
I^{avg}_p	average discrete pump activation index, parameter.
I^{max}_p	maximum discrete pump activation index, parameter.
$I_{p,t}$	discrete activation index, parameter (m^3*kWhr/hr/m/NIS).
$L_{i,j}$	pipe length, constant (m).
N	set of all network nodes.
p	pump station node.
P	set of all pump station nodes.
$Q^t_{i,j}$	flow rate in pipe, variable (m^3/hr).
$Q^t_{p,j}$	flow rate from p to j, variable (m^3/hr).
$R_{i,j}$	pipe resistant's ($C^{-1.852}$ x $D^{-4.87}$ x 10^9 x L), constant.
t	time step index (single hour).
T	set of time indexes.

Tar^{t}_{p}	electrical tariff rate per pump, constant (NIS/kWhr).
T^{DPN}_{p}	set of time indexes that failed discrete pump activation constraint.
T^{DPY}_{p}	set of time indexes subject to discrete pump activation constraint.
TH^{t}_{p}	pump total head, variable (m).
γ	unit conversion, constant (γ = 0.736 / 270).
η_p	pumps overall efficiency (pump, motor and mechanical losses).

2. Methodology

2.1. General

The optimization model developed is an iterative LP (linear programing) solved using GAMS/CLP, an open-source linear programming solver (https://projects.coin-or.org/Clp). The model includes linear water balance and non-linear hydraulic constraints, including varying pump station energy consumption linked to upstream and downstream hydraulic conditions. The convex non-linear headloss and pump energy consumption are iteratively linearized using the convex linearization method presented by Price and Ostfeld (2012). In the above model the pumps are linearly activated during a time step. For example a pump may be activated 0.7 of an hour consecutively for several hours forcing the pump to switch in and out of duty; otherwise frequency control activation may be assumed. If a pump has no frequency control, continues discrete activation schedule would be favored.

The discrete activation is achieved using a constraint that encourages the pump to work fully over a time step in means of a fine incorporated in to the objective function. The algorithm searches for the best time steps in which to discreetly activate the pumps and apply the constraint. A first set holds the pumps time steps in which the constraint is enforced, this set is initially empty. After each iteration step a discrete pump operation index is calculated and the highest scoring time steps are added to the first set. If a pump cannot operate fully in a constrained time step due to water balance or hydraulic constraints, then that pumps time step is transferred to a second set, initially empty, holding time steps in which the constraint failed. The iterative discretization process stops when all time steps in which the pump is activated are in the first or second set. For example, if a pump is required to operate for 4.3 hours consecutively during a 24 hour period, the first 4 hours will be held in the first set and the 5th hour will be held in the second set allowing the pump to partially utilize the time step. The remaining 19.7 hours are held either in the second time step or in neither of the two sets.

2.2. Convex linearization

The convex linearization algorithm replaces the non-linear convex equations of the form [aQ^n+b] with the form [aQ+b], Price and Ostfeld (2013). The linear model is iteratively solved, after each iteration step the linear coefficients a and b of each of the linear equations are modified until a satisfactory approximation to the non-linear equations is reached. The Hazen-Williams headloss equation Eq. (1) is substituted with the linear form in Eq. (2). Pump energy consumption Eq. (3) is substituted with the linear form in Eq (4)

$$dH^{t}_{i,j} = 1.131 \times {Q^{t}_{i,j}}^{1.852} \times {C_{i,j}}^{-1.852} \times {D_{i,j}}^{-4.87} \times 10^{9} \times L_{i,j} \quad \forall(i,j) \in G, \forall t \in T \tag{1}$$

$$dH^{\mathrm{t}}_{\mathrm{i,j}} = \left(\mathrm{Ah}^{\mathrm{t}}_{\mathrm{i,j}} \times \mathrm{Q}^{\mathrm{t}}_{\mathrm{i,j}} + \mathrm{Bh}^{\mathrm{t}}_{\mathrm{i,j}}\right) \times \mathrm{R}_{\mathrm{i,j}} \quad \forall(i,j) \in G, \mathrm{t} \in \mathrm{T} \tag{2}$$

$$E^{t}_{p} = \sum_{j=1}^{N} \left[\left(H^{t}_{j} - H^{t}_{p}\right) \times Q^{t}_{p,j} + R_{p,j} \times {Q^{t}_{p,j}}^{2.852}\right] \times {\eta_{p}}^{-1} \times \gamma \quad \forall(p,j) \in G, \forall t \in T \tag{3}$$

$$E_p^t = \sum_{j=1}^{N} \left[Ap_{p,j}^t \times Q_{p,j}^t + Bp_{p,j}^t \right] \times \eta_p^{-1} \times \gamma \quad \forall (p,j) \in G, \forall t \in T \tag{4}$$

2.3. Discrete pump activation index

A discrete activation index **I** evaluates the best time steps on which to apply a discrete pump activation constraint. The index given in Eq. (5) is calculated by the ratio of flow rate to the cost of pumping the water. The flow rate is given by the variable **Q** and the cost is given by the multiplication of the energy consumption **TH** by the electrical tariff (Tar). Pumping hours with high flow rates and low electrical tariff will receive a higher score then hours with low flow rates during peak electrical tariff periods.

Three time step sets are used. T is a general set holding all the examined time steps (24hr x 365 days). The set T^{DPY}_p holds the time steps per pump in which the discrete activation constraint is applied. The set T^{DPN}_p holds all the time steps per pump in which the discrete activation constraint failed in a previous iteration step. Initially both T^{DPY}_p and T^{DPN}_p sets are empty and gradually fill as the iterative process progresses. The discrete activation index **I** is found for all time steps not included in T^{DPY}_p and T^{DPN}_p. Maximum and average activation index values are given in Eq. (6) and (7).

$$I_{p,t} = \sum_{j=1}^{N} \frac{Q_{p,j}^t}{TH_p^t \times Tar_p^t} \quad \forall p \in P, \forall (p,j) \in G, \forall t \in T, \forall t \notin T_p^{DPY}, \forall t \notin T_p^{DPN} \tag{5}$$

$$I_p^{\max} = \max(t, \varepsilon_{p,t}) \quad \forall p \in P, \forall t \in T, t \notin T_p^{DPY}, t \notin T_p^{DPN} \tag{6}$$

$$I_p^{avg} = \frac{\sum_{t=1}^{T} I_{p,t}}{\dim(T) - \dim(T_p^{DPY}) - \dim(T_p^{DPN})} \quad \forall p \in P, \forall t \in T, t \notin T_p^{DPY}, t \notin T_p^{DPN} \tag{7}$$

2.4. Discrete pump activation constraint

During model solution a discrete pump activation constraint Eq. (8) is applied to pump stations (p) on time steps (t) included in set T^{DPY}_p. For these a slack variable is enforce holding the difference between the pump stations maximum nominal flow rate Q^{max}_p and the flow rate $Q^t_{p,j}$ determined by the optimization model. A substantial fine is imposed on the slack variable in the objective function encouraging the pumps hourly flow rate to equal the pumps maximum nominal flow rate. Part of the objective function is shown in Eq. (9).

$$\sum_{j=1}^{N} \left(Q_{p,j}^t \right) = Q_p^{\max} \times \left(1 - DPslack_p^t \right) \quad \forall p \in P, t \in T_p^{DPY} \tag{8}$$

$$\min \left[\sum_{t=}^{T} \sum_{p=1}^{P} \ldots + DPslack_p^t \times 10^9 \right] \tag{9}$$

2.5. Discrete pump algorithm

The model is solved initially with no discrete activation constraints; sets $T^{DPY}{}_{p}$ and $T^{DPN}{}_{p}$ are empty. After each iteration step, the discrete activation index is calculated using Eq. (5), (6) and (7). Using Eq. (10) time steps with an activation index higher than β the average activation index are added to set $T^{DPY}{}_{p}$. Time steps with a non-zero discrete activation slack variable are removed from set $T^{DPY}{}_{p}$ and added to set $T^{DPN}{}_{p}$, see Eq. (11). A value of β=0.618 was found to return fastest convergence results.

$$if\ (I_{p,t} \geq \beta \times I_p^{\max})\ then\ \{t \in T_p^{DPY}\} \quad \forall p \in P, \forall t \in T, t \notin T_p^{DPY}, t \notin T_p^{DPN} \tag{10}$$

$$if\ (DPslack_p^t > 0)\ then\ \{t \notin T_p^{DPY}, t \in T_p^{DPN}\} \quad \forall p \in P, \forall t \in T_p^{DPY} \tag{11}$$

$$\sum_{p=1}^{P}\left(I_p^{avg} + \sum_{t=1}^{T} DPslack_p^t \right) = 0 \tag{12}$$

The algorithm ends when the average activation index and slack variable equal exactly zero, Eq. (12). This meaning that all the time steps in which the pump is activated are held in sets $T^{DPY}{}_{p}$ or $T^{DPN}{}_{p}$ and in the remaining time steps the pump is not active.

3. Example application

3.1. Model description

The discrete pump activation algorithm was evaluated over a 24 hour period using an example application shown in Figure (1). The application includes a single water source, a pump, a water tank and a single consumer. The consumer has an hourly demand of 900 m^3/hr over 10 hours (between hour 7 to 16) and a minimal water head demand constraint of 91 m, absl. The pump has a nominal flow rate of 1,000 m^3/hr and needs to operate for 9 hours to supply the consumer's daily demand. The water tank has a volume of 5,000 m^3 with a water level between 90 to 100 m, absl. The water head at the water tank node changes linearly relative to the water volume.

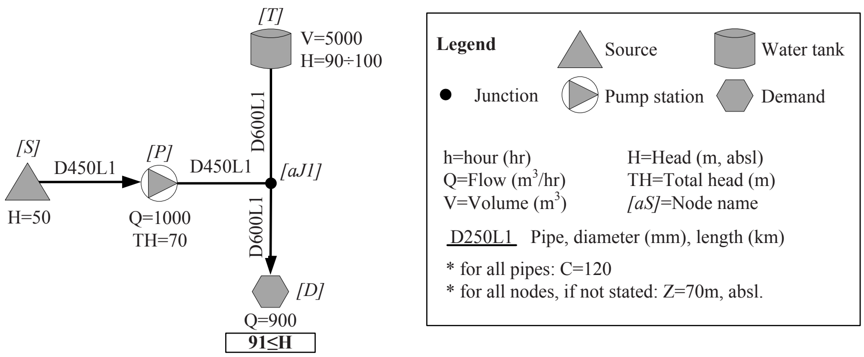

Figure 1 – Example application

3.2. Enumeration (case 1)

The enumeration was performed using an application written is C#. The application preforms a binary count of all possible pump operation combinations (2^{24} = 16,777,216). For each combination, the water balance and the water heads at the nodes were calculated. Combinations not meeting exactly nine pumping hours and a water head at the demand node higher than 91m were discarded. All possible combinations were scanned in 1.06 minutes; 1,290,848 combination meet 9 working hour of which 144,056 combinations also meet the minimum consumer water head constraint, these results are marked acceptable. The different acceptable combinations returned an operating cost between 1,065.9 NIS (New Israeli Shekel) and 1,641.0 NIS. The minimal operating cost was given by 210 combinations. Table 1 shows an optimal pump scheduling combination with an operating cost of 1,065.9 NIS. The displayed pump schedule has the closest resemblance to the solution given in the following case 2. The row marked 'activation' show the pump partial activation per hour, and the row marked 'cost' hold the pump hourly operating cost.

Table 1 – Example application, enumeration results (case 1)

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Elec Tariff period	L	L	L	L	L	L	L	M	M	M	P	P	P	P	P	P	P	M	M	M	M	L	L	L
NIS/kWhr	27.89	27.89	27.89	27.89	27.89	27.89	27.89	43.16	43.16	43.16	100.9	100.9	100.9	100.9	100.9	100.9	100.9	43.16	43.16	43.16	43.16	27.89	27.89	27.89
Case 1 - Enumeration																								
Activation (hr)	**1.00**	-	-	-	-	-	-	-	**1.00**	**1.00**	-	-	-	**1.00**	**1.00**	**1.00**	-	-	-	-	-	**1.00**	**1.00**	**1.00**
Energy (kWhr)	230	-	-	-	-	-	-	-	225	225	-	-	-	207	207	208	-	-	-	-	-	208	215	223
Cost (NIS)	**64.1**	-	-	-	-	-	-	-	**97.0**	**97.3**	-	-	-	**208.4**	**209.1**	**209.8**	-	-	-	-	-	**58.1**	**60.1**	**62.1**
Demand (m3)	-	-	-	-	-	-	-	*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*	-	-	-	-	-	-	-
Pumped (m3)	*1,000*	-	-	-	-	-	-	-	*1,000*	*1,000*	-	-	-	*1,000*	*1,000*	*1,000*	-	-	-	-	-	*1,000*	*1,000*	*1,000*
Wtr,Tank Vol (m3)	*4,000*	*5,000*	*5,000*	*5,000*	*5,000*	*5,000*	*5,000*	*5,000*	*4,100*	*4,200*	*4,300*	*3,400*	*2,500*	*1,600*	*1,700*	*1,800*	*1,900*	*1,000*	*1,000*	*1,000*	*1,000*	*1,000*	*2,000*	*3,000*

The pump was activated for 4 hours in the low tariff period (L), 2 hours in the moderate tariff period (M) and 3 hours during the peak tariff hours (P). The water tank's volume changed between 1,000 m^3 and 5,000 m^3. The hourly relation between the pump's energy consumption (kWhr) and the water tank's volume (m^3) is shown in table 1.

3.3. Iterative linearization with discrete pump activation (case 2)

The example application was solved using the iterative discrete pump activation linearization model. The resulting optimal operating cost is 1,068.1 NIS and is shown in Table 2. The resulting operating cost is greater than the best enumeration result by only 0.2%, see row marked 'cost' in table 2. The optimal pump scheduling is almost the same as the resulting pump scheduling in case 1; with the minor difference of 0.05 hr pump activation in hour 7 on the account of that in hour 0.

Table 2 – Example application, discrete pump activation results (case 2)

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Elec Tariff period	L	L	L	L	L	L	L	M	M	M	P	P	P	P	P	P	P	M	M	M	M	L	L	L
NIS/kWhr	27.89	27.89	27.89	27.89	27.89	27.89	27.89	43.16	43.16	43.16	100.9	100.9	100.9	100.9	100.9	100.9	100.9	43.16	43.16	43.16	43.16	27.89	27.89	27.89
Case 2 - Iterative linearization model - discrete activation																								
Activation (hr)	**0.95**	-	-	-	-	-	-	**0.05**	**1.00**	**1.00**	-	-	-	**1.00**	**1.00**	**1.00**	-	-	-	-	-	**1.00**	**1.00**	**1.00**
Energy (kWhr)	214	-	-	-	-	-	-	9	225	226	-	-	-	207	208	209	-	-	-	-	-	209	216	223
Cost (NIS)	**59.8**	-	-	-	-	-	-	**3.8**	**97.2**	**97.5**	-	-	-	**208.9**	**209.7**	**210.4**	-	-	-	-	-	**58.2**	**60.3**	**62.3**
Demand (m3)	-	-	-	-	-	-	-	*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*	-	-	-	-	-	-	-
Pumped (m3)	*950*	-	-	-	-	-	-	*50*	*1,000*	*1,000*	-	-	-	*1,000*	*1,000*	*1,000*	-	-	-	-	-	*1,000*	*1,000*	*1,000*
Wtr,Tank Vol (m3)	*3,995*	*4,945*	*4,945*	*4,945*	*4,945*	*4,945*	*4,945*	*4,945*	*4,095*	*4,195*	*4,295*	*3,395*	*2,495*	*1,595*	*1,695*	*1,795*	*1,895*	*995*	*995*	*995*	*995*	*995*	*1,995*	*2,995*

The water tanks volume varies between 995 m^3 to 4,945 m^3 over the 24-hour period. The resulting discrete optimal operation schedule is insignificantly different from the result of the best global result found by enumeration.

3.4. Iterative linearization (case 3)

The example application was solved using the basic iterative linearization model with linear pump activation. The resulting optimal operating cost is 955.7 NIS, shown in Table 3. The pump is activated for 2.22 hours during the peak electrical tariff period, 2.70 hours during the moderate period and 4.08 hours during the low tariff period. The partial hourly activation allows the optimal usage of the water tanks volume, minimizing the operating cost of the system. Hour 5 is an example of an unhealthy, short activation of the pump for 15.6 minutes.

Table 3 – Example application, iterative linearization results (case 3)

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Elec Tariff period	L	L	L	L	L	L	L	M	M	M	P	P	P	P	P	P	P	M	M	M	M	L	L	L
NIS/kWhr	27.89	27.89	27.89	27.89	27.89	27.89	27.89	43.16	43.16	43.16	100.9	100.9	100.9	100.9	100.9	100.9	100.9	43.16	43.16	43.16	43.16	27.89	27.89	27.89
Case 3 - Iterative linearization model																								
Activation (hr)	**0.82**	**-**	**-**	**-**	**-**	**0.26**	**-**	**0.70**	**1.00**	**1.00**	**-**	**-**	**-**	**0.04**	**1.00**	**1.00**	**0.18**	**-**	**-**	**-**	**-**	**1.00**	**1.00**	**1.00**
Energy (kWhr)	177	-	-	-	-	48	-	145	230	231	-	-	-	6	206	207	28	-	-	-	-	208	216	223
Cost (NIS)	**49.4**	**-**	**-**	**-**	**-**	**13.4**	**-**	**62.6**	**99.3**	**99.7**	**-**	**-**	**-**	**6.1**	**207.8**	**208.8**	**28.2**	**-**	**-**	**-**	**-**	**58.0**	**60.2**	**62.2**
Demand (m3)	-	-	-	-	-	-	-	*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*	*900*	-	-	-	-	-	-	-
Pumped (m3)	*820*	-	-	-	-	*260*	-	*700*	*1,000*	*1,000*	-	-	-	*40*	*1,000*	*1,000*	*180*	-	-	-	-	*1,000*	*1,000*	*1,000*
Wtr,Tank Vol (m3)	*3,916*	*4,736*	*4,736*	*4,736*	*4,736*	*4,736*	*4,996*	*4,996*	*4,796*	*4,896*	*4,996*	*4,096*	*3,196*	*2,296*	*1,436*	*1,536*	*1,636*	*916*	*916*	*916*	*916*	*916*	*1,916*	*2,916*

4. Summary

The proposed discrete pump activation algorithm using an iterative linearization model was demonstrated on a basic example application including minimal water head at consumer nodes and water balance constraints. A comparison was made between the optimal result returned by the proposed algorithm (case 1) and the results of an enumeration preformed on all pump activation combinations (case 2). The results of both technics were similar to within 0.2% difference in operating costs. Both technics were compared to an iterative linearization model (case 3) which returned an optimal operating cost lower by 11.8% then the first two cases.

The linear scheduling model returns low operating costs but allows partial hourly operation of the pumps. This pump operation increases the switching of the pump on and off causing access mechanical wear. The discrete operation has higher operating costs due to the discrete nature of the pump operation but results in a uniform pump operation.

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